Evaluation of experimentally measured non-stationary oscillations in gyrotrons using adequate simulation methods

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***Abstract* — In order to properly simulate cases in which gyrotrons exhibit fast temporally varying oscillations, such as non-stationary oscillations or possible dynamic After-Cavity Interaction (ACI), an adequate model for the beam-wave interaction has to be used. We will show that the commonly used assumption of considering a constant wave-field envelope during the electron transit time has to be abandoned. The appropriate model (reduced 1D Particle-In-Cell (PIC) model) is briefly presented and the implications of using an inadequate model are illustrated. For the case of a 150W/260GHz gyrotron, non-stationary simulations with the new model will be compared to experiment and used in order to investigate the underlying mechanism of these oscillations.**

I. Introduction

GYROTRONS are medium- to high-power microwave sources based on the Electron Cyclotron Maser (ECM) instability with frequencies in the range from several GHz to above 1THz. They are widely used in plasma heating, but also increasingly in other applications as e.g. in Nuclear Magnetic Resonance (NMR) spectroscopy [1]. Under certain conditions, these devices show the appearance of non-stationary oscillations, which are characterized by temporal variations of the RF-power and a multi-frequency or broadband frequency spectrum. This is the case in the strongly nonlinear regime, where repetitive non-stationary oscillations are observed when the electron beam current significantly exceeds the starting current, but also in the case of dynamic After-Cavity Interaction (ACI) which has been claimed based on simulations of high-power gyrotrons for plasma heating [2].

In order to properly simulate such temporally varying oscillations, the model describing the beam-wave interaction in the cavity-resonator has to be consistent with this situation. Many commonly used models are not applicable to this case, because they are based on the approximation of a constant wave-field envelope during the electron transit time through the interaction region:

$$\Delta\omega_F \sim \frac{1}{|\hat{F}|}\left|\frac{\partial \hat{F}}{\partial t}\right| \ll \frac{v_z}{L} \sim \Delta\omega_{ib} \quad (1)$$

Here, the left side of the inequality sign represents the frequency-bandwidth of the rf-field, corresponding to the rate of change for the field envelope $\hat{F}$. The right-hand side represents the inverse transit time of an electron (parallel velocity v_z) through the interaction region (length L), corresponding to the instability bandwidth of the oscillator. Models based on condition (1) are appropriate for stationary (single-frequency) regimes or in slow non-stationary regimes as long as Eq. (1) is satisfied. In the cases discussed here however, the time scale of field variation is of the same order or faster than the electron transit time and condition (1) is violated.

Several cases, in which a model without condition (1) has to be used, have been described in recent publications and have been analysed after adapting the simulation model for this purpose [3-5]. It has been mentioned in earlier publications by the authors of this contribution [3,6,7], and confirmed by others [5], that earlier results on non-stationary oscillations should be treated with caution, if condition (1) is not satisfied. The issue of using the appropriate model for properly describing multi-frequency oscillations has equally been addressed with respect to dynamic ACI. It has been emphasized in recent publications [8,3], that also for treating this case properly in simulations, an appropriate model valid beyond assumption (1), together with the appropriate broadband non-reflecting wave boundary condition [9], has to be used.

II. Results: Model Comparison

The model used in this paper is extensively presented in [3] and is based on a reduced 1D Particle-In-Cell (PIC) model which solves the slow-timescale self-consistent wave particle interaction equations for a single transverse mode. In the PIC model implemented in the TWANG-PIC code, the particles and fields are simultaneously advanced in space and time and therefore allow to overcome the limitation described by Eq. (1).

We will demonstrate the necessity of using TWANG-PIC for simulating a gyrotron designed for Dynamic Nuclear Polarization (DNP) – NMR spectroscopy. Here different kinds of strongly non-stationary oscillations were observed experimentally, including equidistant sidebands with ns-pulsed RF-power as well as chaotic fluctuation [6,11]. These oscillations are characterized by a power variation with a timescale similar to the electron transit time.

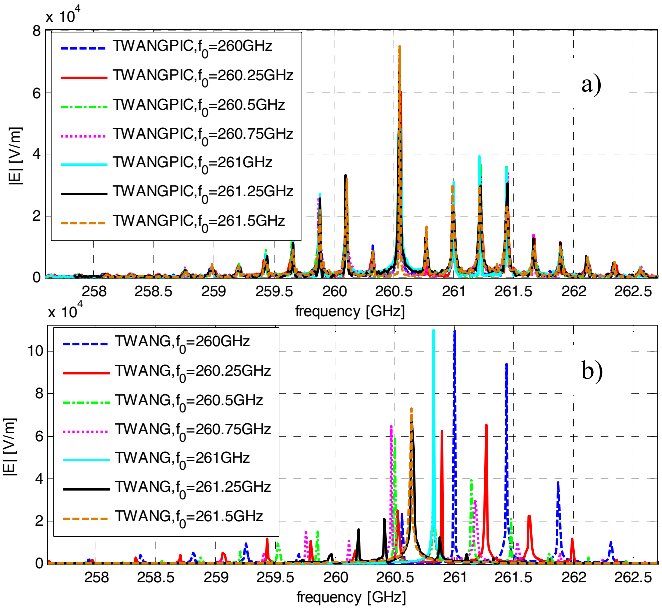

Figure 1: Spectra from a) TWANG-PIC and b) TWANG for the non-stationary operating point (B_0 = 9.60T, I_b = 67mA, α = 1.9). The different line styles and colors correspond to different reference frequencies f_0 (see legend).

For this case, Fig. 1 compares the simulation results of

TWANG-PIC with those of TWANG, which fulfills Eq. (1), on a non-stationary operating point, using different reference frequencies in the simulation (colors and line styles).

The TWANG-PIC results prove to be independent of the simulation parameter reference frequency, while TWANG shows a strong dependency on this parameter. In a stationary oscillation with a single frequency, the reference frequency can be iteratively adapted to the rf-frequency, thus converging to the correct result. For a multi-frequency oscillation however, this dependency cannot be circumvented and renders the results unreliable. This was observed to be a practical implication of the more abstract concern of using an inappropriate model for the beam-wave interaction.

The non-stationary oscillation regime of this DNP-NMR gyrotron has been analysed in an earlier study, using the inadequate model implemented in TWANG [12]. These simulations have recently been re-performed with TWANG-PIC, of which study we will present the main results. An example of this is shown in Fig. 2, which shows a comparison of gyrotron rf-power and frequency between simulation (TWANG and TWANG-PIC) and experiment with additional illustrations of the simulation results. The shown results represent a scan in beam-current I_b for a certain magnetic field value in the forward-wave regime. For simulations, an electron pitch angle α=2.3 was used. This pitch-angle is higher than the value predicted by the electron-optics simulation code DAPHNE [13], but due to experimental indications regarding the appearance of reflected electrons, this value is believed to be close to the actual pitch-angle in experiment. Experimental values for the power are multiplied by a factor 2, which in part is designated to compensate for an underestimating measurement technique.

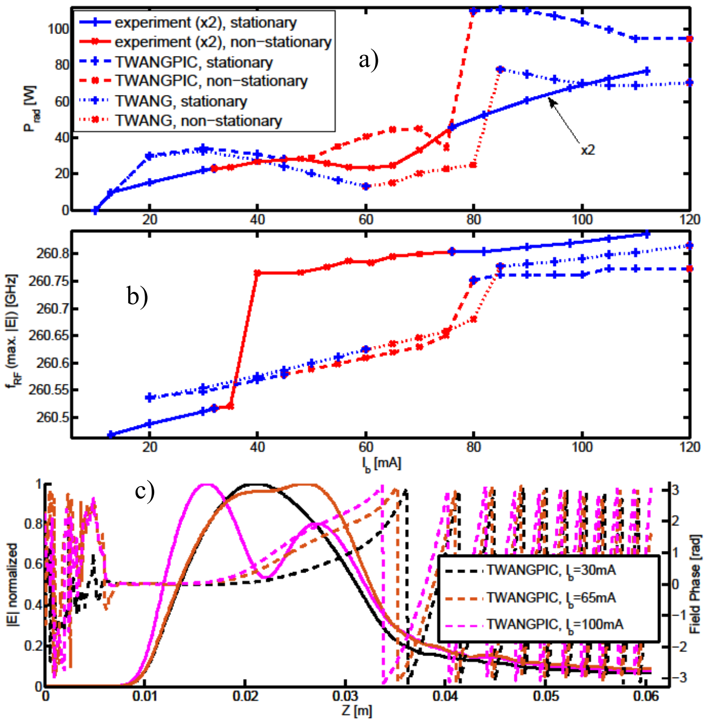

Figure 2: a) RF-Power and b) main frequency (highest peak in spectrum) from experiment (solid), TWANG-PIC (dashed) and TWANG (dotted) for a magnetic field of B_0 = 9.54T and a cathode / anode voltage V_c=15.5kV / V_a = 8.8kV (simulation: pitch-angle α=2.3). The measured power from experiment has been multiplied by a factor 2. Simulations: Reference frequency f_0=260.507GHz. Stationary oscillations in blue/'+', non-stationary oscillations in red/'x'. c) TWANG-PIC field amplitude (solid) and phase (dashed) profile for certain values of the current I_b.

It is observed that the results of TWANG-PIC are closer to the experimental values, especially since the range of beam current, over which non-stationary oscillations are observed, is significantly smaller from TWANG.

TWANG-PIC, TWANG and experiment show qualitatively the same results with a transition from stationary to non-stationary and back to stationary. Interestingly, inside the non-stationary regime, the radiated power decreases with an increasing current and increases abruptly at the upper limit of the non-stationary regime. At the same time, the main frequency (highest peak in spectrum) is observed to perform a jump within (experiment) or after (simulation) the non-stationary regime. This already gives an indication on the origin of the sidebands, namely a change of the nature of beam-wave interaction with an altered field structure and bunching along the interaction region, inside the non-stationary regime. This is illustrated by Fig. 2c) showing the field profile from TWANG-PIC for different values of the beam current. It can be observed, that for I_b =30mA, where the power shows a local maximum, the field profile resembles a q=1 longitudinal mode. Inside the non-stationary regime, the field profile varies in time and is in-between q=1 and q=2-profile, while for higher currents (I_b =100mA), where the frequency and power are increased, a q=2-like profile is observed. The change of field profile seems to be related to this non-stationary regime.

III. Conclusion

These results clearly illustrate, that possibly appearing non-stationary oscillations, violating assumption (1), can only be treated by the appropriate model implemented in TWANG-PIC. At the same time they illustrate how simulations with such an appropriate model can be used for experiment interpretation and give insight into the physical processes governing these oscillations.

Acknowledgments

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References

[1] G. S. Nusinovich et al., *J. of Infrared, Millimeter, and THz-Waves, 35, 325-381, (2014).*

[2] A. Schlaich et al., *36th Int. Conf. on Infrared, Millimeter and THz-Waves (IRMMW-THz), (2011).*

[3] F. Braunmueller et al., *Physics of Plasmas, 22, 063115 (2015).*

[4] N.S. Ginzburg et al., *Physics of Plasmas, 22, 033101 (2015).*

[5] O. Dumbrajs and H. Kalis, *Physics of Plasmas, 22, 053113 (2015).*

[6] S. Alberti et al., *Physics of Plasmas, 19, 123102 (2012).*

[7] F. Braunmueller et al., *39th Int. Conf. on Infrared, Millimeter and THz-Waves (IRMMW-THz), (2014).*

[8] K. A. Avramidis et al., *Physics of Plasmas, 22, 053106 (2015).*

[9] S. Alberti et al., 'Generalized radiation boundary conditions in gyrotron oscillator modeling', *to be submitted to Journal of Infrared, Millimeter and Terahertz Waves.*

[10] S. Alberti et al., *36th Int. Conf. on Infrared, Millimeter and THz-Waves (IRMMW-THz) (2011). .*

[11] S. Alberti et al., *Phyical Review Letters, 111, 205101 (2013)*

[12] F. Braunmueller et al., *38th Int. Conf. on Infrared, Millimeter and THz-Waves (IRMMW-THz), (2013).*

[13] T. M. Tran et al., *6th Joint EPS-APS International Conference on Physics Computing, Petit-Lancy, p.492 (1994).*